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QUENCH DEVELOPMENT IN MAGNETS MADE WITH MULTIFILAMENTARY NbTi CABLE

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SUMMARY

An experimental study of the normal zone propagation and total resistance as a function of time is described. The normal zone propagation velocity in a single strand was measured as a function of both current and magnetic field with particular interest in the neighborhood of the short sample limit. The study proceeded from measurements in single multifilamentary strands to measurements in 23 strand cables under different cooling environments to finally measurements in actual ramping dipole magnets made with this cable. Interpretation of the results led to the determination of safety limits for the Energy Doubler/Saver magnets and to safeguards implemented by an energy dumping circuit which effectively protects these magnets from self-destruction.

I. INTRODUCTION

Toward the goal of understanding in detail the quenches in the high current density ramping dipole magnets of the Energy Doubler, this experimental study of a quench development with time was made. The stability criteria[1,2] and calculations[3,4] in the literature are helpful to this understanding but not sufficient for the determination of realistic safety limits since the actual heat exchange coefficient of the cable is a function of position and hard to describe.

The technique used is based on recording simultaneously the current and the voltage drops across several strategically situated 2.54 cm lengths of the superconductor with a fast multichannel chart recorder. From these measurements and the distances involved we obtained the velocity of propagation, the power dissipated and the resistance as a function of time. A similar technique was independently used by L. Dresner et al.[5]

II. SINGLE STRAND MEASUREMENT

The quench propagation velocity of a single superconducting strand was measured as a function of both the electrical current in the strand and an external magnetic field. The strand is composed of 2100 filaments of NbTi (53.5% niobium and 46.5% titanium by mass) with 9 µm diameter. The filaments are imbedded in a 686 µm diameter copper matrix, which gives it a 1.8 ratio of copper to superconductor cross sectional area.

The strand was immersed in pool boiling liquid helium and the quenches were initiated by the discharge of a capacitor into a heater wrapped around the strand at one end. The propagating quench was detected at three fixed points 15.24 cm apart by observing the voltage drop across 2.54 cm of strand at each point. The three voltages were recorded by a millivolt chart recorder at 200 mm/sec. The current and field were varied and in some cases the quenches were self initiated. The result is shown in Fig. 1 and it is consistent with the idea that the heat needed to raise the temperature above the critical temperature is supplied by the power dissipated just behind the wave front.

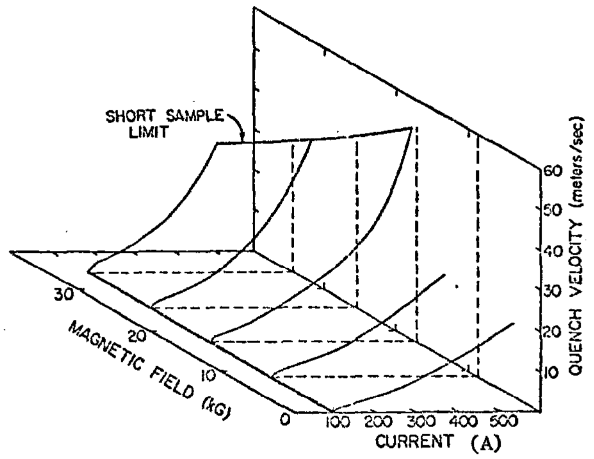

Fig. 1. Quench velocity for a single strand as a function of current and magnetic field.

III. 23 STRAND CABLE MEASUREMENT

The superconducting cables used to wind the Energy Doubler/Saver magnets are made by twisting 23 of the above strands with a pitch of 6.62 cm into a two layer, .127 x .762 cm rectangular cross section cable. The quench propagation velocity was measured for this cable under no external magnetic field and in two different cooling environments. The results are presented in Fig. 2.

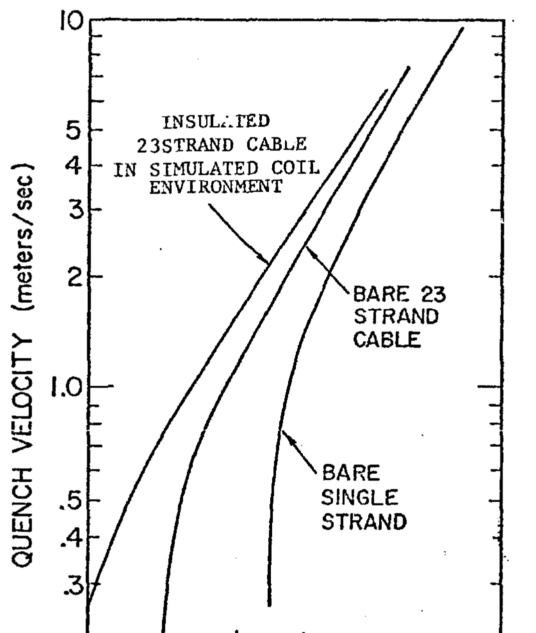

Fig. 2. Quench velocity as a function of current. The single strand current has been multiplied by 23 for purpose of comparison.

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The bare single strand exhibits the lowest velocity, the bare 23 strand cable exhibits an intermediate velocity, and the insulated cable with simulated coil environment exhibits the highest velocity. There is a large difference in quench velocity at low currents, where cooling plays an important part, but it is interesting to note that the difference, although somewhat diminished, still persists up to high currents. The velocity of quenches in our prototype magnets, occurring at the high field point, is 14±1 meters per second.

IV. MEASUREMENTS IN A 30 CM LONG DIPOLE MAGNET

The voltage drops between nine different voltage taps near the high field point, in a one foot Doubler prototype magnet, were observed during a quench using the technique described above. A typical plot of the time sequence of different sections going normal yields the map of the quench wavefront shown in Fig. 3. The primary origin is indicated and a secondary origin is also indicated. The secondary origin was in thermal

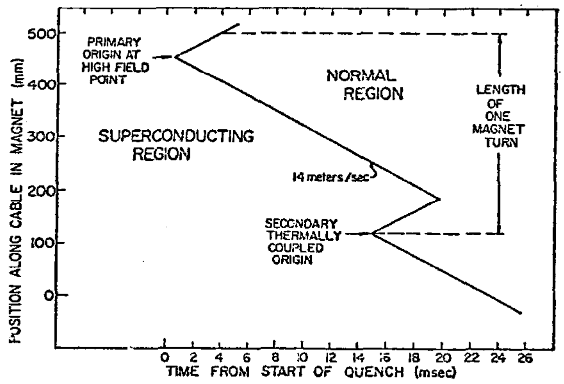

Fig. 3. Development of a double quench.

contact with a conductor that had already gone normal in the first turn. The jumping of quenches from turn to turn implies a transverse quench velocity which is two orders of magnitude lower than the longitudinal velocity. Similar investigations performed on other magnets indicate that several primary quenches may start at separate locations at almost the same time.

The above technique was also used to locate the origins of quenches during the training of this prototype magnet. Figure 4 indicates that indeed the quenches do originate near the high field point.

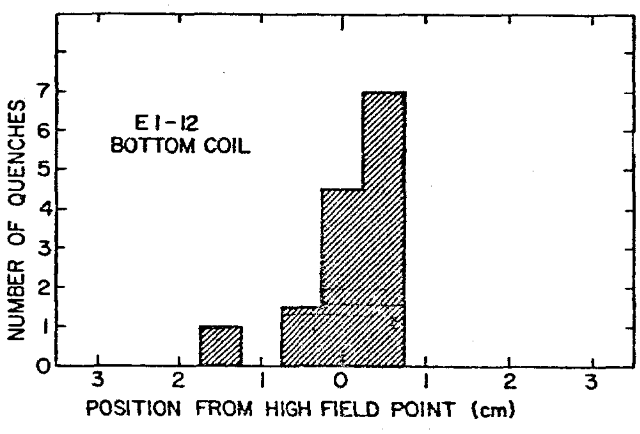

Fig. 4. Distribution of quench positions.

V. MEASUREMENTS IN A 3 METER LONG DIPOLE MAGNET

During the training of the 10 foot Doubler prototype magnet, E10-2, the energy dissipated in the magnet as a function of time was calculated from the chart recordings by integrating the power dissipated with respect to time. In no case did the total energy dissipated exceed 10% of the energy stored in the magnetic field. The energy, E, which was dissipated in the magnet varied greatly from quench to quench, as shown in Fig. 5.

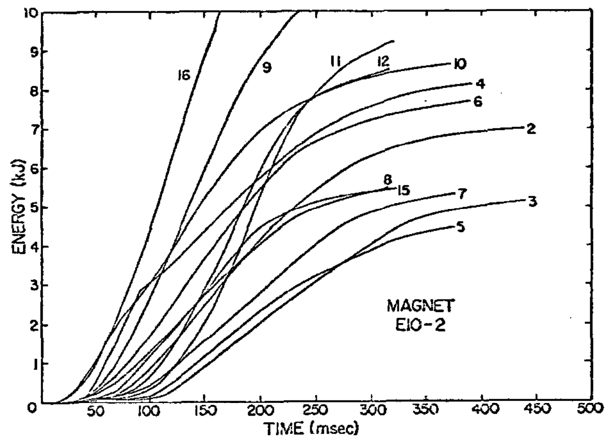

Fig. 5. Energy dissipated internally during a quench. The numbers identify the quenches in a sequence.

A plot of the instantaneous resistance developed as a function of the instantaneous energy dissipated in the magnet is presented in Fig. 6. The straight line drawn in this plot expresses the relation $R=2.3E^{.65}$

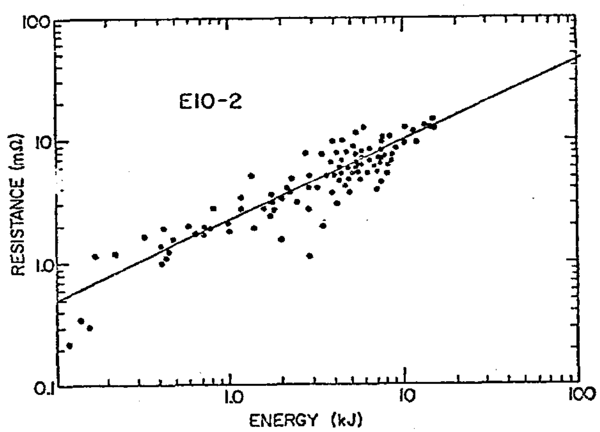

Fig. 6. Internal instantaneous resistance developed during quenches of magnet E10-2.

VI. SAFETY CONSIDERATIONS

A conservative design criteria for magnet protection is that the energy deposited in any volume of the wire should be insufficient to raise its temperature above a safe value T under the worst cooling conditions namely, no cooling.

Let A, μ, ρ(θ) and c(θ) respectively be the cross sectional area, density, resistivity, and specific heat of a small element of conductor at temperature θ. The energy deposited per unit length of conductor when a time dependent current i(t) flows through it causes a temperature rise dθ according to energy balance equation:

$$\mu\, c(\theta)d\theta = \rho(\theta)\,\frac{i^2(t)}{A^2}\,dt \tag{1}$$

The maximum temperature T attainable by this element of wire can be obtained from the integration of (1):

$$\mu A^2 \int_{4.2K}^{T} \frac{c(\theta)}{\rho(\theta)}\,d\theta = \int_{0}^{\infty} i^2(t)\,dt \tag{2}$$

The right hand side of this expression can be appropriately called "quench load". The left hand side is a function of the wire expressing a "quench capacity".[6]

Two simple computer programs were developed to guide our understanding. Both make use of a description of the cable and of literature values for the specific heat of the components to build an expression for $c(\theta)$ as well as measured[7] values of $\rho(\theta)$. The first program (QCDVAN) calculates the left hand side of (2). The result is presented in Fig. 7 as the maximum attainable temperature T versus the corresponding quench load.

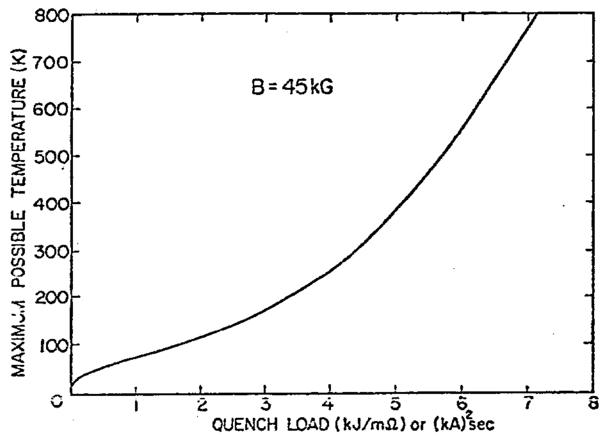

Fig. 7. Quench heating as calculated by program QCDVAN

The temperature climbs very fast at first because the specific heat is very low at low temperatures. Above 30K the temperature climbs rather slowly due to increased specific heat. The gradual pick up at room temperature and above reflects a stationary specific heat and an increasing resistivity. Corrections due to magneto-resistance effect amounts to an increase in T of only a few percent.

Comparing the QCDVAN predictions and actual quenches it was easy to correlate the tests that resulted into damage to a magnet with "quench loads" corresponding to temperatures above melting solder.

The second computer program (HOTCM) was made to simulate the temperature and resistance increase as a function of time for 1 cm of the cable. It uses a current i(t) representative of the ones observed in actual quenches. This program therefore provides a description of what happens in the worse case (no cooling) to the hottest centimeter of the cable during a quench of the magnet.[8]

Comparing the HOTCM predictions and the observed performance we concluded that this no cooling condition is reasonably observed during the short duration of a quench. The transfer of the energy from the magnet into an external dump resistor was implemented with SCR switching,[9] using the circuit given in the appendix.

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APPENDIX

The circuit[10] used to energize and fastly de-energize the superconducting magnet into a 200 mΩ water immersed resistor is shown in Fig. 8.

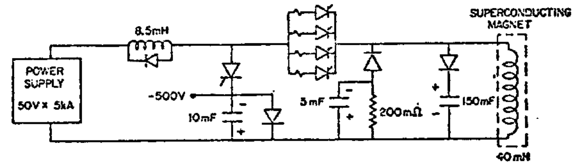

Fig. 8. Energy dumping circuit.

In normal operation the current goes through the series inductor, the series SCR bank and the superconducting magnet. When the beginning of a resistive voltage rise is detected across the magnet leads, the single SCR is fired causing the series SCR bank to commutate off and the magnet current is diverted to the 200 mΩ dump resistor.

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